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Wave power—Sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters

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ABSTRACT

Generating electricity from waves is predicted to be a new source of renewable energy conversion expanding significantly, with a global potential in the range of wind and hydropower. Several wave power techniques are on the merge of commercialisation, and thus evoke questions of environmental concern. Conservation matters are to some extent valid independent of technique but we mainly focus on point absorbing linear generators. By giving examples from the Lysekil project, run by Uppsala University and situated on the Swedish west coast, we demonstrate ongoing and future environmental studies to be performed along with technical research and development. We describe general environmental aspects generated by wave power projects; issues also likely to appear in Environmental Impact Assessment studies. Colonisation patterns and biofouling are discussed with particular reference to changes of the seabed and alterations due to new substrates. A purposeful artificial reef design to specially cater for economically important or threatened species is also discussed. Questions related to fish, fishery and marine mammals are other examples of topics where, e.g. no-take zones, marine bioacoustics and electromagnetic fields are important areas. In this review we point out areas in which studies likely will be needed, as ventures out in the oceans also will give ample opportunities for marine environmental research in general and in areas not previously studied. Marine environmental and ecological aspects appear to be unavoidable for application processes and in post-deployment studies concerning renewable energy extraction. Still, all large-scale renewable energy conversion will cause some impact mainly by being area demanding. An early incorporation of multidisciplinary and high quality research might be a key for new ocean-based techniques.

Contents

1. Introduction

Infrastructure projects have by definition some impact on the environment, including nature conservation issues. Most new renewable energy (RE) conversion could be labelled as "outspread" infrastructure projects and can be characterized by today's

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development of wind power. Wind power, a method of generating electricity is provoking debates on a number of issues in several countries. However, the recent focus on RE is to a large extent dependent on climatic change and CO_2 emission although several other factors may also play an important role for the development of RE. Those include replacement of older electricity generating plants such as old fossil fuel dependant electricity generation, depleting oil and gas sources and most important, a steady increase in energy demands, most notably in some Asian countries. All taken together, RE is already one of the fastest growing industrial branches in the world.

The theoretical potential for wave- and tidal energy conversion is immense in parts of the world with long oceanic coastlines [1]. The physical properties of waves make them a very interesting source of energy, being better in comparison with e.g. wind and solar power, due to higher energy density and more predictable occurrence (solar influx is converted to wind that in its turn is converted and stored as waves) [2]. Wave power along the European west coast has been estimated to be able to cover all of the Western European electric energy consumption [1,3]. Recently, there have even been estimations on wave energy conversion also in milder climate sea areas indicating an even greater worldwide availability for wave power [4,5]. Although the techniques are generally not as far developed yet, it is likely that wave power will become at least as important as wind and hydropower are today [6]. As a consequence a growing number of wave power projects will also set focus on the ecological impacts and conservational aspects. Therefore, ecologists and engineers together must consider environmental effects from wave and other offshore power installations. Aims should be to get a good overview of possible impacts as well as being able to contribute with knowledge and recommendations for a sustainable development in the early stages. It is important to stress the need for a good theoretical background as well as the need for good applications for future conservational work. Unfortunately, RE and its implications for the local environment have gained far too little attention among ecologists. Thus, it is an important start to emphasise on investigating RE, and to understanding the costs and benefits of RE for the environment. Despite an increasing scientific focus on RE during the last decades the proportion of ecologically related matters remains sparse as shown by the low number of peer-reviewed articles found [7]. There are no existing deeper evaluations within and between different RE sources.

All large-scale RE conversions are area demanding and therefore in a potential conflict with other interests. For example, wind power parks may pose a threat to nature conservation, either through loss of habitat [8,9], disturbance or direct mortality [10]. Wind power parks often have problems with NIMBY (“Not in my backyard”), and a number of studies indicate that birds, bats and mammals may avoid wind power areas due to disturbance [11,12]. Growing turbine sizes, larger parks with newly created hard substrates will lead to novel problems for future offshore wind power projects and cumulative impact on several issues. In some countries this is followed closely by strong governmental input (e.g. Denmark and Great Britain) whereas other countries appear not to produce any pre- or post-construction studies of scientific value.

Wave and tidal power projects are still in the development stage with only some projects having reached demonstration status and a few closing in on commercialisation. Moreover, there is more than one technique employed today with most of them being structures on the surface [13]. Some of the well-known examples of full-scale wave energy converters (WECs) include offshore devices like the Archimedes Wave Swing [14], the Pelamis [15], and the Wave Dragon [16]. Overtopping constructions are mostly shoreline devices, i.e. techniques that require over-flushing waves, and examples are TAPCHAN and OWC’s, such as the Pico or the LIMPET [17].

Commercial wave- and tidal energy ventures will undergo application and evaluation processes similar to other large-scale energy projects, including Environmental Impact Assessments (EIAs). The environmental requirements on wave power projects will be similar to other large offshore projects, if not tougher as demands are likely to increase. Yet, ongoing environmental baseline studies are taking the advantage from experiences from other offshore ventures, i.e. choice of suitable areas, study methods or estimation of environmental impacts on specific sites [18].

In this paper we are emphasising on the nature conservation aspect related to wave power. These are matters also expected to become included in EIAs, and several related questions are likely to appear as key issues. The impacts from human activities on the ecology in an area may happen rapidly, but are not be easily predictable and consequently demand long-term studies. Unfortunately, the ecological knowledge of the marine biota is relatively poor compared to terrestrial ecosystems. Moreover, studies in marine environments, especially offshore and in deep waters are costly and require advanced underwater technologies. Consequently, the demand to investigate positive as well as negative effects in the marine environment will be a challenge and require cooperation between ecologists and engineers.

To illustrate this we describe the newly started marine ecological studies on effects from point absorbing linear wave generators within the Lysekil project off the Swedish west coast [19,20]. In this project the environmental and technical aspects are studied hand in hand, and thus environmental aspects may influence final technical solutions. Investigations on how the new technique of point absorbing WECs and the marine environment are influencing each other are important in order to plan for larger scale projects further off the coast. Finally, we will also list a few recommendations for future studies on offshore devices based on a priori knowledge.

2. General issues

Apart from nature conservation aspects and site-specific environmental issues (e.g. red-listed species), recommendations for suitable sites for wave power generators are well covered in the Wave Hub (2006) compendia. These include avoidance of shipping lanes, areas of military importance, and marine archaeological sites (including world war 2—wrecks and dump sites). Other potential conflicts include areas set aside for mining or for dredging of sand and gravel. Existing pipelines and cables further restrict establishment of wave power, although most likely on a smaller scale. Already existing offshore activities limit future establishments, including offshore wind power parks, oil and gas fields. Wave- and tidal powers are less likely to interfere with recreation such as leisure boats, since parks may be placed far off the coast.

The Lysekil research site is a wave power park under development on the Swedish west coast since 2005. The wave power units consist of steel-buoys on the surface that, via wires, drive translators in directly driven linear generators [19–21]. The generators are moored to concrete foundations, placed on the seabed (Fig. 1). The working range for this type of device is between a depth of 20 and at least 100 m [21]. The Lysekil research site is situated about 2 km off the coast and the buoy area will, fully built out, consist of 40 U, 10 with generators and additional 30 for environmental studies, and cover about 40 000 m^2 (Fig. 2). The depth at the site is 25 m and the seabed is a transport-bottom consisting of sandy clay and shell-sand located at the southern tip of the marine Gullmarsfjorden Natura 2000-reserve [22].

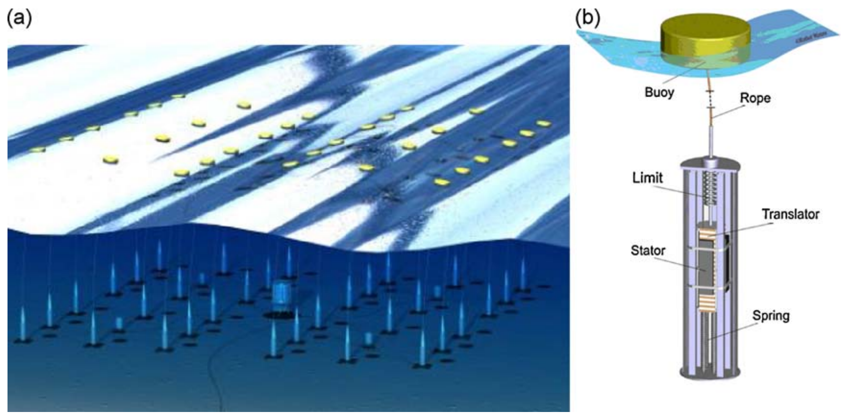

Fig. 1. Illustration of a section of a wave power park with (a) several smaller units of wave energy converters and (b) a detailed illustration of a single unit © Seabased AB.

3. No-take zones and artificial reef effects

Wave- and tidal power, independent of technique, will hinder most commercial fishing, especially with trawls and nets and will most likely become an issue in larger offshore establishments. For instance, an installation of 1000 linear wave energy converters requires an area of ca. 1 km^2, an area that inevitably will be lost as fishing ground. From the nature conservation perspective the scenario may be completely different. No-take zones are a growing demand from most conservationists and ecologists as most seas are overexploited, so a total cessation of commercial fishing may be positive for fishery management strategies [23]. Thus the development of wave- and tidal parks, that will prohibit fishing in these areas, may enhance fish populations, fish size and species richness, comparable to marine protected areas [24]. Disturbance through fishing and dredging have immense negative effects on local species diversity and population density and recolonisation of the disturbed areas can take from months up to years [25–27]. The formation of marine reserves, where fishing is prohibited, has in fact been found to result in an increase in fish density, diversity and abundance also in adjacent areas, for the benefit of local and commercial fishing [28–31].

Once the deployment phase is over, when sound disturbance is inevitable, environmentally positive effects of offshore energy parks may outweigh the potential negative impacts. Still, we are in need of long-term studies regarding noise during both deployment and operation phases. However, the foundations of wind- and wave power devices will function as so-called secondary artificial reefs (ARs), locally enhancing biomass for a number of sessile and motile organisms [32–34]. Solid structures placed in seawater most often become attractive to marine organisms in terms of ARs lying on the seabed. The artificial substrates may induce both physical and biological changes on soft-bottom habitats. Physical changes that might occur are alterations in currents and waves; this may alter sediment-size distribution which may favour the accumulation of organic material in this area [35]. Biological changes might be alterations in biodiversity, species abundance and biomass [36–40]. Still, there are conflicting results regarding whether this increase in biodiversity is a result of aggregation from the surroundings or a true increase in species and biomass [41,42]. Higher species abundance due to ARs have been suggested to be related to better protection from predation, new food sources, increased feeding efficiency and an enhancement in larval recruitment [43]. The calculated production attributable to the AR effect was about nine times higher than the estimated production of bottom-dwelling fish [36]. At specific sites ARs may provide a method for long-term lobster enhancement, assuming habitat to be a major limiting factor for the population size [44]. On the other hand, the introduction of new substrates may also introduce new species which might influence the existing ones through other patterns of competition, predation and parasitism. Possibly, this is only a problem if the offshore installation is located close to areas that are important to protect, such as estuaries and nature reserves, or if rare and red-listed species are found in or close by the installation. Normally most species of invertebrates and fish occur as larvae or fry in the pelagic zone and substrate is the most important factor in determining eventual settling of larvae. However, artificial structures will never host exactly the same species as a natural hard substrate [45–47].

Fig. 2. The Lysekil research site during summer 2008 with several devices for ecological studies and one generator buoy in the centre © Swedish Centre for Renewable Electric Energy Conversion.

In the Lysekil project we assume that species living in the area or in the near vicinity of the research site will be affected by concrete foundations, used for anchoring the generators. The presence of wave power devices in this area, dominated by a homogenous soft-bottom, will increase the complexity of the area with its hard substrate surfaces. Thus the devices will inevitably have the function of ARs.

Studies of species composition, their change and abundance in the sediment are ongoing and proceed during and after deployment of the test park. Monitoring studies in the Lysekil research site before construction began showed that the most abundant organisms in the sediment are polychaetes, followed by molluscs and echinoderms [20]. No red-listed species have yet been found in this area and there is no concern about local extinction of rare species as the area of the research site is small. If disturbed, most benthic organisms living in this area are expected to recover quickly during and after the deployment. Small opportunistic species such as polychaetes and amphipods are the quickest to colonise after disturbance, while epifaunal species assemblages need more time to colonise [26,48]. On soft substrata changes happen more rapidly than on coarse sediment, which is more stable and thus changes occur more slowly [49].

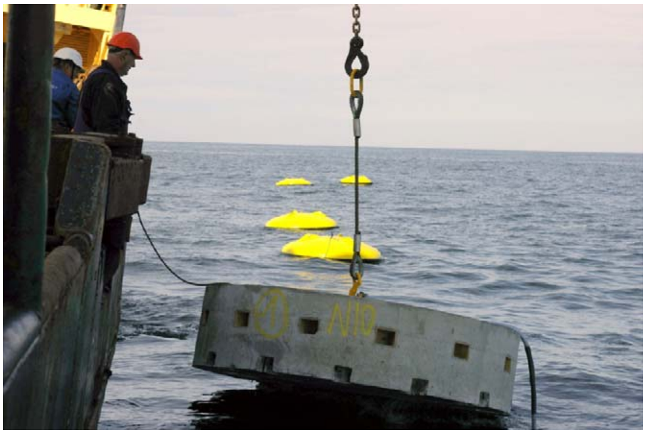

Fig. 3. Deployment of experimental wave power foundation with enhanced structural complexity for fish and crabs during spring 2007. In the background four of the environmental buoys. Photo: O. Langhamer © Centre for renewable electric energy conversion.

One important research topic is an effective and purpose-built reef design. For ecological experiments at the Lysekil research site, foundations with higher complexity were placed out (Fig. 3). This catered for commercially interesting species, i.e. crabs and lobsters [32,50]. Is the reef-effect desired or is a minimal change in biodiversity and abundance wanted? Since hard substrate is a good basis for larval recruitment from the water mass and for migration of juvenile and adult marine organisms, it can be expected that fish, crabs and lobsters from nearby natural habitats will be observed on and in these foundations [44]. Animals from the surroundings may easily find new habitats due to shelter and food sources which contribute to better growth and reproduction. Thus new species composition following from higher total biomass, biodiversity and species abundance can be expected in this area. Data from earlier studies support the hypothesis that species abundance is proportional to the degree of complexity, shade and structural volume of the artificial reef [51–53]. A complex substratum increases the spatial heterogeneity which can increase the species diversity of an area by providing more ecological niches, allowing more animals to recruit [54]. The value of structural complexity seems to be related to several things such as ambush possibilities for predators, shelter for prey, the presence of organisms attached to or hiding between the structures that may serve as food, or a combination of these factors [53]. Due to these shelters and a no-take zone, the Lysekil test site, in our case, may also function as a nature protection area. Since the potential for habitat development and protection is high, the application of foundation technology to nature conservation issues needs to be emphasised.

It has been shown that floating structures on the water surface attract both juvenile and adult fish [55,56]. There are several hypotheses to explain why fish aggregate around floating devices. Protection from predators, availability of food, seabed substitute, spawning substrates, cleaning stations and resting areas are examples of these hypotheses [56]. Since the buoys in our test site act as fish aggregation devices (FADs), fish are expected to gather around them in high numbers and a great diversity. Questions and studies related to fish populations will be important. Still, full-scale studies on fish will require employment of a larger number of buoys, but will start before the project is fully built up. Thus the area may become more attractive to neighbouring organisms and contribute to higher species diversity similar to the artificial reef effect as mentioned above. In general, putting out new structures may lead to new trophic opportunities and changes in local food web interactions due to new habitat availability [57]. Finally it is important to determine if the new structures are beneficial to existing indigenous species or if they attract non-indigenous species that alter the species composition [58]. In order to study how the quantity of fish and their behaviour is influenced by the Lysekil research site, fishing and diving observations are and will be conducted. Species will be identified; their size and feeding preferences analysed in order to examine positive or negative changes in occurrence and behaviour.

4. Biofouling and sedimentation

Gravity foundations placed on the seabed may have relatively local impact on the marine environment. During the deployment phase, stirring sediments lead to suspended particles which may thus affect feeding behaviour of fish, fish larvae and suspension feeders. Eggs, algae and benthic organisms may get buried and suppressed [59]. The amount and concentration of suspended particles may vary due to hydrodynamics and topography.

The fact that new structures will be attractive for sessile marine organisms may become a technical burden, known as marine biofouling. From a biological perspective this can be positive but costly for offshore projects due to increased maintenance or even undesired mechanical wear that requires costly antifouling measures. On ideal constructions biofouling has little impact on performance. The use of antifouling paints etc should also be avoided as older paint contains metals such as lead and copper. Many newer paints have been criticised for having less or no function although new research on barnacles show that natural biochemicals may be effective deterrents [60,61].

Important fouling organisms on buoys and buoy lines are blue mussels, barnacles, algae, hydroids, tubeworms and sea stars [62]. The question is whether it is bad for the efficiency of the wave power buoys to be overgrown by biofouling. The fouling contributes to higher species richness and diversity in the area and thus has a positive ecological effect. But it can have negative technical impacts on buoy material, weight, shape and thus on the efficiency of wave-absorbing. A quantification of biofouling has been made within the Lysekil project during the summer of 2005 and 2006, using marking buoys as a model to investigate how much growth can be expected [32]. Estimates on the amount of biomass that may attach to buoys indicate that as much as 150 kg of biomass may be added per buoy with a diameter of 3 m. In a large park of thousands of buoys this could be an issue, hypothetically. The calculated model can be used to modify buoy shape, and indicates that perhaps biofouling has no negative impact on the lifting force of a buoy. Thus, the simplest and cheapest solution would be to let biofouling grow on the wave energy converters. Since growth on the buoys may be followed by high sedimentation rates in the research site, sedimentation may become an issue in wave and tidal power projects. In the artificial habitat, an increase in the sedimentation rate of the mineral fraction and of the organic fraction is expected from direct and indirect sedimentation of the epiphytic biomass. These sedimentological and ecological transformations can induce eutrophication of the benthic ecosystem and can lead towards lower biodiversity and reduction in trophic levels [63]. However, WECs being placed in deep waters along with even slight currents is likely to make this a minor problem.

5. Migration

Wind projects usually are set with a focus on birds and bats, as they are seen to be threatened the most due to their migration patterns and collision risks [10–12]. Seabirds have been shown to gather around oil platforms and rigs in high numbers due to food accumulations and night lighting. Since there are no projecting formations on the wave power devices compared to wind power

generators, birds' behaviour and migration have a low potential to be affected negatively [18]. Thus, birds and bats are unlikely to become an issue in most tidal- and wave projects. An exception might be shoreline devices close to breeding colonies that can destroy or disturb nesting sites or feeding grounds. Studies in the Lysekil research site may bring answers to whether birds are also likely to gain from WECs as resting sites that could also serve as feeding habitats. In a review article, Gill [7] pointed out that the threat to coastal and migratory birds mostly depends on number, size and spacing of the devices and their moving parts. But there are rarely any studies of marine fauna and their collision risk with or avoidance of offshore energy devices [64]. Thus the foreseen impact on mobile aquatic species poses some question marks, but it is unlikely that wave power devices result in direct mortality. In tidal energy devices, however, rotating underwater turbines have the potential of being more harmful, but it will mainly depend on rotation speed and turbine designs [65]. In a hydropower study of Dadswell and Rulifson [66], a decline in fish abundance of 20–80% per passage was shown depending on fish species, fish size and the efficiency of turbine operation. They suggested that introduction of tidal turbines into open-ocean zone current systems will cause widespread impact on marine populations. Similarly, large areas covered by e.g. buoys may function as extensive movement-barriers. This may be most prominent for migratory species or species that cover large areas during foraging, which most marine mammals do. Areas for spawning, resting and nursing may be destroyed. Unfortunately, little is known about corridors that migrating fish and marine mammals use. Moreover, these routes may in fact be irregular and unpredictable, and are likely to be dependant on, for instance currents, season, regional and local climate and access to food resources. Yet, this will be a question likely to require answers in most attempts to find good locations for wave- and tidal energy conversion and thus calls for literature- and field studies along with applications for permits and deployment.

6. Underwater noise and electromagnetism

Another area that has become a topic in recent years is marine underwater noise, known not only to affect seals, dolphins and whales, but also several species of fish [67–69]. Large number of species of different taxa (cetaceans, pinnipeds, teleosts, crustaceans) use underwater sounds for interaction, like communication, finding prey and echolocation, locating recruitment sites in fish, finding mates, and avoiding predators [70–74]. Many marine organisms like e.g. whales and seals may be sensitive to disturbance connected to construction of sites or during maintenance (e.g. Sundberg [75], Faber Maunsell and Metoc [76]) but habituation, i.e. animals getting used to novel structures and human presence, should not be ruled out. The production of noise by drilling and placing during construction, cable laying, as well as boat traffic can damage the acoustic system of species within 100 m from the source and mobile organisms may thus avoid these areas during that time [48]. Noise can also mask important natural sounds or perhaps stress if strong enough [76,77], but little is known about the long-term effects of noise on individuals and on populations [67]. Earlier studies on offshore wind power showed that marine mammals are able to detect the low-frequency sound generated by the wind-turbines [68]. Behavioural reactions of marine mammals to noises due to construction and operation of offshore installations are highly variable since marine organisms are often exposed to many different noise-sources [73]. It ranges from attraction (e.g. bow riding by dolphins) or no response through short-term changes in behaviour to short-or long-term displacement. Clearly, wave and tidal power plants have to be constructed taken conservation issues into account. Gill [7] suggested analyses of spatial and temporal behaviour of sensitive species that inhabit or migrate through the coastal environment together with the measurement of acoustics. Field observations out at sea require ships, divers or even permanent platforms from which work can be done. The use of advanced technologies will therefore be required in order make field observations possible, ideally remote controlled. This will include different kinds of sonar, sound recorders, video (both above and under surface), possibly also radar along with a number of meteorological and hydrological data collectors. However, recent findings indicate that the use of sonar may affect marine mammals and recent research suggests that the use of high beam sonar, used by navies may cause "stranding" in whales [78–80]. Such findings call for an open mind when employing new techniques that in fact may cause impact rather than helping in research as first intended. In the Lysekil research site, work related to placing of gravity foundations on the seabed may have a low effect on acoustic sensitive organisms. Harbour seals may be affected during construction as several haul-out sites, i.e. rocks and isles used for resting exist within a short distance. During operating phase seals and harbour porpoises have regularly been observed at the test site (pers. observations).

Electromagnetism is a topic appearing in almost any new wind power project and it is likely to reoccur in future wave power projects. Some marine animals like migratory fish, elasmobranches, chelonians, crustaceans and marine mammals use the Earth's magnetic field for navigation [64,81–83]. In a study of Bochert and Zettler [84], long-term exposure of different species of benthic organisms to static magnetic fields was investigated without finding any effect on survival and reproductivity. Fish seem not affected to any significant degree by sea cables and their electromagnetic field [85–87]. But still, it is unknown if sensitive species are attracted or repelled by magnetic and electric fields, and if their behaviour patterns may be changed. With the use of a better cable technique the electromagnetic fields only affect the nearest surroundings as the background earth magnetic field usually becomes more prominent only a few decimetres from the cable. In combination with cables buried into the seabed this problem might disappear.

7. Before-after/control-impact

When setting up environmental studies, including those related to EIAs and follow-up studies, the choice of methods and technique is important. The scientifically approved methodology in most cases is Before-After/Control-Impact (BACI [88]) stressing the importance of starting studies prior a project in order to have data to compare with after a construction is completed. Monitoring carefully selected environmental parameters during construction and operation will lead to more reliability in determining diverse impacts and effects of wave- and tidal parks. The biological world is varying over time and in order to control for local stochastic events, such as locally occurring population trends, the use of control site(s) is essential to avoid misinterpretations. Most marine ecological studies require one or several control areas to be able to distinguish between natural or human induced changes that occur during a longer time period. In the case of the Lysekil project there is a suitable area with same quality and depth that is located just outside the actual test site. Ongoing population studies on dynamics and interactions of organisms colonising the buoy area will give more information about the establishment of marine communities and their productivity. If positive this can be important in conservational aspects and lead to a better socio-economic acceptance. One aim with the Lysekil test park is to gain knowledge that may lead to a greater understanding of habitat design, protection and uses for scientific experiments, used as an integrated management tool.

8. Conclusions

We are convinced that much can be gained by early incorporation of environmental studies in the Lysekil project as a whole. Long-term studies should be conducted focusing on effects and impacts relating to single units as well as, in the Lysekil project, the future formation of arrays. First, such studies may give early insight into changes of sessile and motile organisms in the area. Early indications also give the opportunity for early technical alterations or corrections, most likely making wave projects more acceptable in the long run and more suitable for the marine environment. Second, more will be known about habitat requirements of key species, species interactions and energy-flow within and close-by a wave power park. Third, studies focusing on the effect of fouling and artificial reefs will result in knowledge important both for project builders and as well as for conservationists. For particular projects the effects of fouling and the subsequent maintenance needed will have a bearing on project economics.

Finally, we suggest that different wave- and tidal power projects share information on environmental aspects, based on BACI if possible. Such knowledge will contribute to most projects, speeding up application process and to some extent reducing the need to repeat studies, but foremost it will help good techniques to reach the market and deliver green energy. This could be done in centralised or project-specific databases, or similar. Such databases would also help in making Strategic Environmental Assessment (SEA) analyses, also recently implemented by the European Commission (SEA Directive 2001/42/EC) as an overview tool for societal planning.

A lesson could also be learned from the wind industry development, where it took decades before anything about impacts appeared in peer-reviewed journals and where related environmental studies of a good standard still are unfortunately rare. Thus high quality research is required to increase and disperse knowledge effectively that may lead to better acceptance and sustainability.

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